Detection of negative superhumps in a LMXRB – an end to the long debate on the nature of V1405 Aql (X1916-053)

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ABSTRACT

The detection of two similar periodicities (3001 and 3028 s) in the light curve of V1405 Aql, a low mass X-ray Binary (LMXRB), has attracted the attention of many observers. Two basic competing models have been offered for this system. According to the first, V1405 Aql is a triple system. The second model invokes the presence of an accretion disc that precesses in the apsidal plane, suggesting that the shorter period is the orbital period while the longer is a positive superhump. The debate on the nature of V1405 Aql has been continued until very recently. Re-examination of previously published X-ray data reveals an additional periodicity of 2979 s, which is naturally interpreted as a negative superhump. The recently found 4.8-d period is consequently understood as the nodal precession of the disc. This is the first firm detection of negative superhumps and nodal precession in a LMXRB. Our results thus confirm the classification of V1405 Aql as a permanent superhump system. The 14-year argument on the nature of this intriguing object has thus finally come to an end. We find that the ratio between the negative superhump deficit (over the orbital period) and the positive superhump excess is a function of orbital period in systems that show both types of superhumps. This relation presents some challenge to theory as it fits binaries with different components. We propose that a thickening in the disc rim, which causes increased occultation of the X-ray source, is the mechanism responsible for both types of superhumps in LMXRBs. However, the positive signal is related only to the pronounced dips in the light curve, where the point-like central source is covered up, whereas the morphology of the negative superhump signal appears quite smooth, implying obscuration of a larger X-ray emitting region, possibly the inner accretion disc or a corona. According to our model superhumps (both in the X-ray and optical regimes) are permitted in high inclination LMXRBs contrary to Haswell et al. (2001) prediction.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: V1405 Aql – novae, cataclysmic variables

1 INTRODUCTION

1.1 Permanent superhumps

Permanent superhumps have been observed so far in about 20 cataclysmic variables (CVs) (Patterson 1999). These show superhumps (quasi-periodicities shifted by a few percent from their orbital periods) in their optical light curves during normal brightness state. In contrast, SU UMa systems (see Warner 1995 for a review of SU UMa systems and CVs in general) have superhumps only during their bright dwarf nova outbursts (superoutbursts).

Permanent superhumps can either be a few percent longer than the orbital periods and they are called '**positive superhumps**', or shorter – '**negative superhumps**'. The positive superhump is explained as the beat between the binary motion and the precession of an accretion disc in the apsidal plane. Similarly, the negative superhump is under-

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stood as the beat between the orbital period and the nodal precession of the disc (Patterson 1999).

According to theory, superhumps are developed when the accretion disc extends beyond the 3:1 resonance radius and becomes elliptical (Whitehurst & King 1991). Osaki (1996) suggested that permanent superhump systems differ from other subclasses of non-magnetic CVs in their relatively short orbital periods and high mass-transfer rates, resulting in accretion discs that are thermally stable but tidally unstable. Retter & Naylor (2000) gave observational support to this idea. Simulations suggest that superhumps can only occur in binary systems with small mass ratios – $q = M_{donor}/M_{compact} \lesssim 0.33$ (Whitehurst 1988; Whitehurst & King 1991; Murray 2000). Although this condition is easily met in short orbital period LMXRBs, whose primaries are compact massive objects, superhumps have been only seen in a few LMXRBs in outburst (e.g. O'Donoghue & Charles 1996). Here we report the detection of permanent superhumps in a persistent LMXRB.

1.2 V1405 Aql (X1916-053 / 4U 1915-05)

V1405 Aql was first discovered as an X-ray source showing type-I bursts (Becker et al. 1977; Doxsey et al. 1977) suggesting that its primary star is a neutron star. White & Swank (1982) and Walter et al. (1982) independently found ∼3000-s periodic dips in its X-ray light curve. The dips are believed to occur due to obscuration of the disc edge (probably where the accretion stream impacts the disc). Such a short orbital period implies a low mass hydrogen-deficient secondary star (Nelson, Rappaport & Joss 1986). The 21-mag optical counterpart of V1405 Aql was identified by Schmidtke (1988) and Grindlay et al. (1988). They also reported a detection of an optical periodicity, about one percent longer than the X-ray period. The difference between the X-ray and optical periods was confirmed by further extensive observations of V1405 Aql (Smale et al. 1988; 1989; 1992; Callanan 1993; Callanan, Grindlay & Cool 1995; Yoshida et al. 1995; Church et al. 1997; 1998; Ko et al. 1999; Morley et al. 1999; Chou, Grindlay & Bloser 2001; Homer et al. 2001).

The various models offered so far for the periodicities found in V1405 Aql can be grouped into two basic models – a triple system (Grindlay 1986; Grindlay et al. 1988) and superhumps (Schmidtke 1988; White 1989). According to the first model, which was motivated by the detection of a possible 199-d periodicity in the X-ray light curve of V1405 Aql (Priedhorsky & Terrell 1984), the longer 3028-s period is the binary inner orbital period, while the shorter 3001-s period is the beat between the binary period and the ∼4-d orbital period of a third companion. The 199-d period is explained by the eccentricity of the inner binary orbit (Chou et al. 2001). The second model suggests that the 3001-s period is the binary period and that the 3028-s period is a positive superhump. We note that both models predict the presence of a beat periodicity of ∼4 d. Indeed evidence for a period of ∼3.9 d has been found in the X-ray light curve of V1405 Aql (Chou et al. 2001; see also Homer et al. 2001).

The debate on the nature on V1405 Aql has continued (Chou et al. 2001; Homer et al. 2001; Haswell et al. 2001), although some preference was given to the superhump scenario. One of the arguments against the triple system model is that the 199-d period was not confirmed by further obser-

vations, although a second possible evidence for this periodicity was found by Smale & Lochner (1992). On the other hand, an argument against the superhump model is that the 3028-s period is quite stable while superhump periods are unstable (Callanan et al. 1993; 1995; Chou et al. 2001; Homer et al. 2001).

There is a strong observational link between positive and negative superhumps in CVs as light curves of several systems show both (Patterson 1999; Arenas et al. 2000; Retter et al. 2002b). In addition, Patterson (1999) found that period deficits in negative superhumps are about half period excesses in positive superhumps: $\epsilon_- \approx -0.5\epsilon_+$, where $\epsilon = (P_{superhump} - P_{orbital})/P_{orbital}$. Thus, we decided to look in available photometric data on V1405 Aql for negative superhumps, which would be predicted to have a period near 2986 s. Indeed we have found a new periodicity in the X-ray light curve of V1405 Aql. These findings were reported by Retter, Chou & Bedding (2002a), and are presented below. We also present a new relation for systems that have both types of superhumps, and discuss the mechanisms for superhumps in the X-ray and optical regimes.

2 OBSERVATIONS AND ANALYSIS

We have re-analysed existing X-ray photometry that was presented by Chou et al. (2001). The dataset consists of about 150 ksec of observations by the RXTE satellite obtained during 17 occasions between 1996 February to October.

In Figs. 1a & 2a the power spectrum (Scargle 1982) of 10 successive runs in 1996 May is presented. No de-trending method was used. Bursts were not observed during these observations. In addition to the two known periods (3001 & 3028 s, marked as f_1 & f_2) and their 1-d^{-1} aliases, there is a third peak (labelled f_3) together with its 1-d^{-1} alias pattern. After fitting and subtracting the first term of the two known frequencies (f_1 & f_2), the third, which corresponds to the periodicity 0.034483±0.000013 d (2979.3±1.1 s), becomes the strongest peak in the residual power spectrum (Figs. 1b & 2b). The error was calculated by 1000 simulations (see e.g. Retter et al. 2002b). The subtraction of nine more terms of the periods (to account for a non-sinusoidal shape) and the 3.9-d period (whose peak in the raw power spectrum is not significant) yields similar results. This point is valid for all tests listed below. The power spectrum of the whole 1996 dataset resembles the result of the 10 runs in May, however, it is noisier as the gaps between the observations are long.

In Fig. 3 we show the mean shape of the 2979-s period in 1996 May. The full amplitude of the sinusoidal fit to the light curve is 8.0±1.2 counts/sec, which translates to 25±4% of the mean count rate. This is smaller than the mean amplitude of the 3028-s period – 28±4% and the mean depth of the 3001-s dips – 35±5%. The superposition of these three signals can explain the deepest observed dips that sometimes reach almost 100% (i.e. total obscuration).
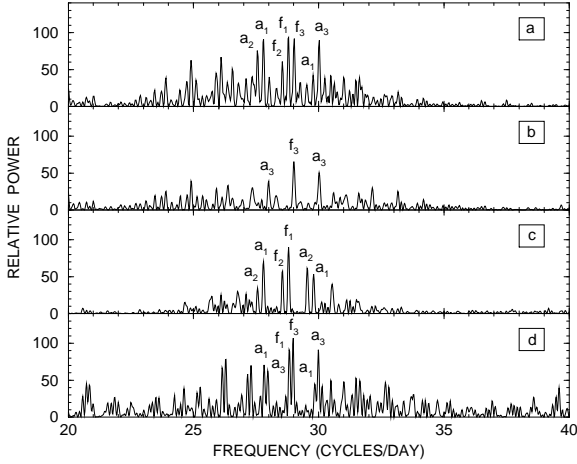
2.1 Tests

Figure 1. Power spectra of 10 successive runs in 1996 May: **a**. Raw data; In addition to the two previously known periods – the 3001-s period (marked as f_1) and the 3028-s period (f_2), there is a third structure of peaks centered around 2979 s (f_3); 'a_i' (i=1-3) represent 1-d^{-1} aliases of 'f_i'. **b**. After fitting and subtracting f_1 and f_2, f_3 becomes the strongest peak in the power spectrum. **c**. Power spectrum of a synthetic light curve, consisting of sinusoids of the two known periods (plus noise) sampled as the data thus illustrating the window function. **d**. Same as (a), after rejecting the dips.
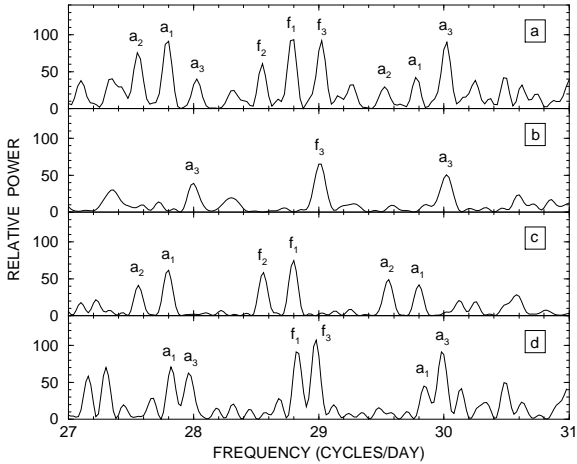

Figure 2. Same as Fig. 1, zoomed into the periods.

2.1.1 The window function

To check whether the third peak in the power spectrum could be an artifact of the window function, a noiseless simulation of the 1996 May set was created. A synthetic light curve was built using two sinusoids at the 3001 and 3028-s periods. These sinusoids were given the same amplitudes they have in the data and sampled according to the window function. There was no evidence for significant power at the proposed period.

2.1.2 Uncorrelated noise

In an attempt to check whether uncorrelated noise could be responsible for the presence of the new peak in the power
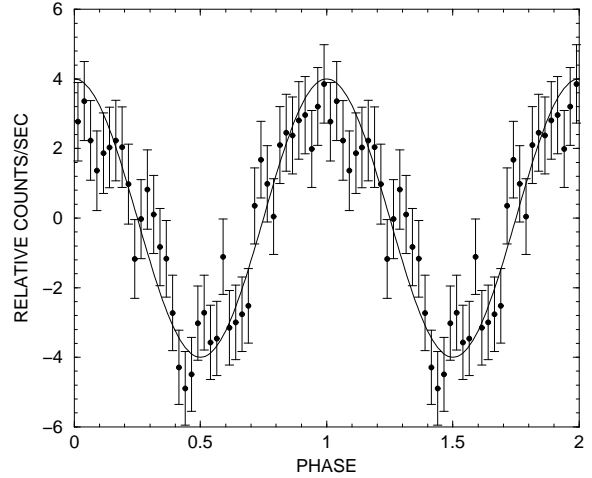

Figure 3. The data folded on the 2979-s period and binned into 40 bins. The solid line represents the sinusoidal fit to the data.

spectrum, the two previously known periods (3001 and 3028 s) were subtracted from the data. The remaining points, assumed to be white noise, were shuffled randomly between the timings. A power spectrum was calculated for each random configuration. The highest peak at the range f=20-40 d^{-1} in 1000 simulations did not reach the height of f_3.

In a different test, that checks the significance of a third peak in the presence of two others, we took the synthetic light curves (see previous section) and now added noise, defined as the root mean square of the original data minus the periods modelled. We then searched for the highest peak in a small interval (28.9-29.1 cycles/day) around the candidate period (f_3). The lower value is dictated by the nearby presence of the 3001-s period (f_1). In 1000 simulations, no peak reached the height of the candidate periodicity. Figs. 1c & 2c show an individual example of this simulation.

2.1.3 Correlated noise

Another test we tried was to assess the probability that correlated noise could be responsible for the candidate periodicity. In the absence of a model for the correlated noise, the best test is to use the repeatability between different datasets. Thus the 1996 May data were divided into two subsets – the first and last five runs. Power spectra of both sets were calculated after the two known periods (3001 & 3028 s) were removed. Fig. 4 displays the results. In both sets the strongest peak (up to a 1-d^{-1} alias) is very near the peak at the power spectrum of the whole set (Figs. 1 & 2).

Given that we have found a period in the first subset, we can ask how likely it is that the strongest period in the second subset would be consistent with it. The probability of the highest peak in another dataset being, by chance, compatible with the candidate period in the first set is 0.04. This was calculated from (i) twice the frequency error (0.02 d^{-1}) on the peak in the first subset and (ii) the range over which it could occur taken as the spacing of the 1-d^{-1} aliases. This test suggests that the candidate periodicity is 96% significant. We note, however, that the frequency error was calculated by 1000 simulations. A naive estimate of the error as
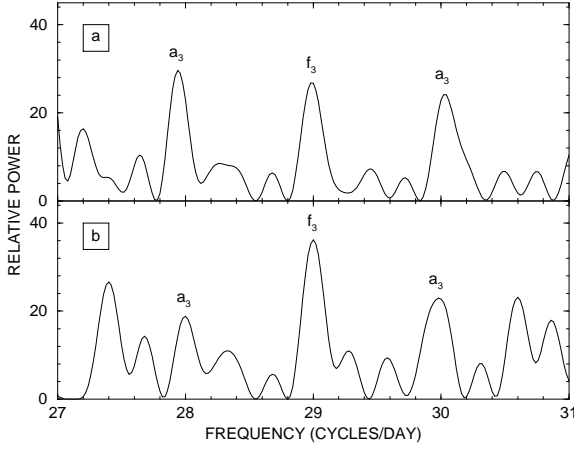
Figure 4. Power spectra of two parts of the 10 successive runs in 1996 May after the 3001 and 3028-s periods have been removed: **a**. First five runs. **b**. Last five runs. In both panels the highest peak or a 1-d^{-1} alias corresponds to the same periodicity.

the width at half maximum of the peak yields a somewhat lower significance level.

2.1.4   The influence of the dips

To eliminate the possibility that the new periodicity in V1405 Aql arises from random variations in the shape, width and / or depth of the dips, all points connected with the dips were manually rejected. The highest peak in the power spectrum of the remaining data is consistent with f_3 (Figs. 1d & 2d). This test shows that the 'persistent' light curve (i.e. without the dips) is dominated by the 2979-s periodicity.

3   DISCUSSION

3.1   The new period

A period of 2979 s has been found in the X-ray light curve of V1405 Aql in addition to the other known periods. This feature was actually noticed by Chou et al. (2001) who mistakenly identified it with a 3.9-d sideband of the 3001-s period. It is, however, $\sim 5\sigma$ away from the expected sideband at 2974.2 s and we have shown above that it is not an alias. We also note that a period of 2984.6 ± 6.8 s was detected in the Ginga data of this object (Smale et al. 1989). As it is inconsistent with either the 3001 and 3028-s periods, it probably represents the new periodicity as well.

The 2979-s period is shorter than the 3001-s period by about 0.7 percent. Assuming that the 3001-s period is the orbital period and that the 3028-s period is a positive superhump, the new period is naturally explained as a negative superhump. Our suggestion implies a nodal precession of ~ 4.8 d. Indeed Chou et al. (2001) found that the phase jitter of the X-ray dips in the 1996 May data is modulated with a period of 4.86 d (as well as with the ~ 3.9-d period). Homer et al. (2001) reached a similar conclusion from a different dataset and found a period of 4.74 ± 0.05 d. Thus, the superhump model can explain this periodicity as well.

The 2979-s period in the X-ray light curve of V1405 Aql and the beat period at ~ 4.8 d cannot be explained by the

Table 1. The periods in V1405 Aql

Number	Period	Nature	Reference
1	2.8 ms	spin	Boirin et al. (2000)
	3.7 ms		Galloway et al. (2001)
2	2979.3(1.1) s	negative	this work
	2984.6(6.8) s	superhump	Smale et al. (1989)
3	3000.6508(9) s	orbital	Chou et al. (2001)
	3000.6(2) s		Homer et al. (2001)
4	3027.5510(52) s	positive	Chou et al. (2001)
	3027.555(2) s	superhump	Homer et al. (2001)
5	3.9087(8) d	apsidal precession	Chou et al. (2001)
6	4.86 d	nodal	Chou et al. (2001)
	4.74(5) d	precession	Homer et al. (2001)

triple system model. This scenario was motivated by the possible detection of the 199-d period that has not been confirmed by further observations (Section 1.2). Homer et al. (2001) suggested a few other possible periodicities (~ 8.6, ~ 12, ~ 23, ~ 83 d) in the X-ray light curve of V1405 Aql. It is very likely that V1405 Aql has random variations of the order of a few tens of day, but not a coherent long-term periodicity. We thus believe that the triple system model for V1405 Aql is finally ruled out.

Table 1 lists the periods observed in V1405 Aql and their interpretations according to the superhump model. The presence of an extensive number of periodicities can explain many peculiarities in the light curve of the system that have been previously discussed by many authors.

3.2   A new relation for superhumps

Patterson (1999) proposed that the negative superhump deficit is about half the positive superhump excess (Section 1.2). As the 3028-s period is about 0.9 percent longer than the 3001-s period, the corresponding ratio in V1405 Aql (0.79) is somewhat larger than this. We have checked the connection between the deficit and excess of negative and positive superhumps in CVs and found a new relation. Table 2 presents the data on the periods in systems showing both types of superhumps. In Fig. 5 we show this ratio for these systems, and we see a clear trend as a function of orbital period. Our result for V1405 Aql fits this trend very well.

3.3   Implications

Our results strengthen the observational link between positive and negative superhumps, and supports the idea that the two types of superhumps have a similar physical origin, namely a precessing accretion disc. Retter et al. (2002b) speculated that every permanent superhump system may have both kinds of superhumps. The data on V1405 Aql support this idea.
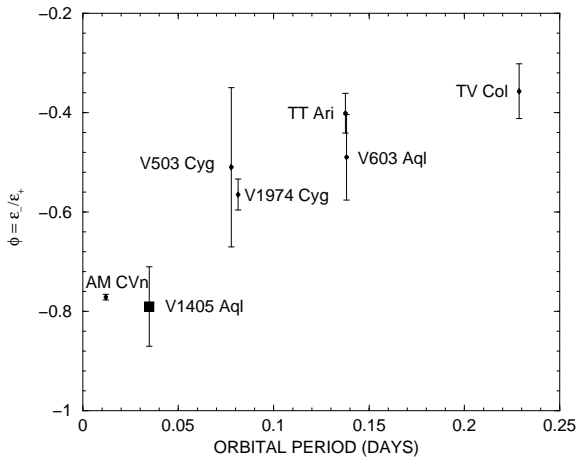
Wood, Montgomery & Simpson (2000) showed that a tilted accretion disc can explain the presence of negative superhumps, however, it is still unclear what physical force

Table 2. Properties of systems that have the two kinds of superhumps

Object	Orbital Period [d]	Positive Superhump [d]	Positive Superhump Excess (ϵ_+)	Negative Superhump [d]	Negative Superhump Deficit (ϵ_-)	$\phi = \epsilon_-/\epsilon_+$	Ref.
AM CVn	0.011906623(3)	0.0121666(13)	0.02183(12)	0.01170613(35)	-0.016839(30)	-0.7714(57)	1,2,3
V1405 Aql	0.034729754(11)	0.035041099(60)	0.0089648(20)	0.034483(13)	-0.0071(7)	-0.79(8)	4,5
V503 Cyg	0.0777(2)	0.08104(7)	0.0430(27)	0.07597(18)	-0.022(5)	-0.51(16)	2,3,6
V1974 Cyg	0.0812585(5)	0.08506(11)	0.0468(14)	0.07915(7)	-0.02644(62)	-0.565(31)	2,3,7,8
TT Ari	0.1375511(2)	0.1492(1)	0.0847(7)	0.1329(3)	-0.034(3)	-0.401(40)	2,3,9
V603 Aql	0.1381(1)	0.1460(7)	0.0572(51)	0.1343(3)	-0.028(2)	-0.490(86)	2,3,10
TV Col	0.22860(1)	0.2639(35)	0.154(15)	0.2160(5)	-0.0551(23)	-0.357(55)	3,11

[1]Skillman et al. (1999); [2]Patterson (1998); [3]Patterson (1999); [4]Chou et al. (2001); [5]This work; [6]Harvey et al. (1995); [7]Retter, Leibowitz & Ofek (1997); [8]Skillman et al. (1997); [9]Skillman et al. (1998); [10]Patterson et al. (1997); [11]Retter et al. 2002b;

Notes to Table 2: 1. V1159 Ori (Patterson et al. 1995), V592 Cas (Taylor et al. 1998), PX And and BH Lyn (Patterson 1999) were rejected from this sample as their superhump periods are still uncertain (Patterson, personal communication). 2. ER UMa (Gao et al. 1999) was not considered as the detection of negative superhumps does not seem secure.

Figure 5. The relation between the orbital period and the ratio between the negative superhump deficit and the positive superhump excess in systems that have both types of superhumps.

drives the disc to precess in the nodal plane (Murray & Armitage 1998). Wynn (personal communication) suggested that a strong magnetic field of the primary white dwarf can cause the disc to precess in the nodal plane. If this idea is confirmed, negative superhumps are expected in every permanent superhump LMXRB, as their primaries have magnetic fields typically much stronger than in CVs.

Montgomery (2001) and Montgomery et al. (in preparation) developed analytic expressions for the two types of superhumps. The theoretical values for the ratio $\phi = \epsilon_-/\epsilon_+$ mentioned above, were found to be consistent with the observations of CVs. Montgomery et al.'s results can also explain the relation shown in Fig. 5 for CVs (see their Fig. 6). Using their equation 9 & Fig. 4 (but baring in mind the difference in primary mass) and the observed ϕ parameter in V1405 Aql (Table 2), we can derive a weak upper limit on its mass ratio of $q \lesssim 0.08$. For a primary neutron star at the Chandrasekhar limit, this implies an upper limit on the mass of the secondary – $M_2 \lesssim 0.12 M_\odot$, which is presumably a helium white dwarf.

The fact that binary systems with very different configurations (CVs – a hydrogen-rich white dwarf and a red companion; AM CVn – two degenerate helium white dwarfs

and V1405 Aql – a neutron star and a helium white dwarf) obey the relation presented in Fig. 5 is quite surprising. It might be a coincidence, or it may suggest that ϕ indeed depends on the orbital period and not on the mass ratio. Further determinations of this parameter in more permanent superhump systems are required to study this issue.

3.4   The mechanism for negative superhumps

The mechanism which places the negative superhump signal into the X-ray light curve is unclear, but changing vertical disc structure seems a promising candidate. It is clear that positive superhumps coincide with increased disc thickness (Billington et al. 1996), the evidence being consistent with the idea that the area of the disc involved in producing the superhump light thickens at the time of the increased dissipation. In the nodal precession model, Wood et al. (2000) showed how the passage of the secondary star past each of the two halves of the disc out of the midplane increases the dissipation in that half. They also required that the side of the disc closest to the orbital plane is the most disrupted. If, by analogy with positive superhumps, this disruption increases the vertical extent of the disc, then it will increase the obscuration of the X-ray source. As the disc precesses, the timing of the obscuration will change with phase, producing the required modulation at the negative superhump period. The lack of structure and large range in phase of the negative superhump modulation implies that both the disc structure and occulted region are large, the latter presumably being the inner accretion disc or a corona. This scenario can also explain why negative superhump signals have not been observed so far in the X-ray light curves of low inclination systems.

3.5   The mechanism for positive superhumps

Haswell et al. (2001) pointed out that the dissipation of energy in the disc, which is believed to be responsible for the positive superhump mechanism in CVs in the optical, cannot be applied to LMXRBs. They suggested that instead the disc area is changing with the superhump period, and thus predicted that superhumps would appear mainly in low inclination systems. Figs. 1 & 2 show that the X-ray data is modulated with the positive superhump (f_2). However,

when the dips are rejected from the light curve, this peak disappears. Thus in V1405 Aql only the dips show the positive superhump, presumably since their amplitude and / or phase vary with the apsidal precession period. Note that the phase jitter of the dips is modulated with the 3.9-d period (Chou et al. 2001). Therefore, a simple explanation of this behaviour is that thickening of the disc rim, which causes an increase obscuration of the X-ray source, forms the positive superhump. This is consistent with our suggestion for the mechanism for the negative superhump in the X-ray (previous section). The disc thickening would allow the disc to intercept more of the irradiating flux, thus producing optical superhump light seen at all inclinations in a similar way to the Haswell et al. area effect. In addition, though, it would introduce dips into the X-ray and perhaps optical orbital light curves, allowing the superhump to be visible in high inclination systems, in contrast to the prediction of Haswell et al.

4   ACKNOWLEDGMENTS

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